GRANT /1R/IN/34

HAMPTON UNIVERSITY

NASA FAR-96 Program

SUMMARY OF RESEARCH

START UP IN FLUID MECHANICS AT HAMPTON UNIVERSITY

NASA Grant, NAG-1 1835

3,5 Year Granted Period

Effective Date: 06/01/96

Expiration Date: 12/31/99

Dr. Morris H. Morgan, III
Principal Investigator
Dean of the School of
Engineering &Technology

Dr. Mikhail M. Gilinsky
Primary Investigator
Research Professor
School of Engineering &Technology

- MARCH 2000 -

ADVANCED METHODS FOR ACOUSTIC AND THRUST BENEFITS FOR AIRCRAFT ENGINE NOZZLES

SUMMARY OF RESEARCH

The Fluid Mechanics and Acoustics Laboratory (FM&AL) was established at Hampton University in June of 1996. The initiation of this laboratory was made possible by NASA grant NAG-1-1835, FAR Award, 1996-99, for which this is the final report, and is supported by the NASA grant NAG-1-1936, FY 1997 Partnership Award, 1997-00. In addition, the FM&AL jointly conducted research with the Central AeroHydrodynamics Institute (TsAGI, Moscow) in Russia under a 2.5 year Civilian Research and Development Foundation (CRDF) grant #RE2-136, 1996-99. The goals of the FM&AL programs are twofold: **1)** to improve the working efficiency of the FM&AL team in generating new innovative ideas and in conducting research in the field of fluid dynamics and acoustics, basically for improvement of supersonic and subsonic aircraft engines, and **2)** to attract promising minority students to this research and training and, in cooperation with other HU departments, to teach them basic knowledge in Aerodynamics, Gas Dynamics, and Theoretical and Experimental Methods in Aeroacoustics and Computational Fluid Dynamics (CFD). The research at the FM&AL supports reduction schemes associated with the emission of engine pollutants for commercial aircraft and concepts for reduction of observables for military aircraft. These research endeavors relate to the goals of the NASA Strategic Enterprise in Aeronautics concerning the development of environmentally acceptable aircraft. It is in this precise area, where the US aircraft industry, academia, and Government are in great need of trained professionals and which is a high priority goal of the Minority University Research and Education (MUREP) Program, that the HU FM&AL can make its most important contribution.

This project already benefits NASA and HU because:
First, the innovation, testing, and further development of new techniques for advanced propulsion systems are necessary for the successful attainment of the NASA Long Term Goals in Aeronautics and Space Transportation Technology (ASTT) including Global Civil Aviation, Revolutionary Technology Leaps, Access to Space, R&D Services, and the economic competitiveness of the US Aircraft Industry in the 21st century.

Secondly, the joint theoretical and experimental research and training by the GRC-HU Teams aids: using advanced methods and experience in Aerospace Engineering for domestic industries and training of HU students for interesting innovative work in the numerical simulation field as well as engineering and experimental research. HU students use and modify existing numerical codes for the solution of actual applied problems of the NASA Langley Research Center (LaRC).

The main achievements for the reporting period in the development of concepts for noise reduction and improvement in efficiency for jet exhaust nozzles for aircraft engines are as follows:

1) Publications: The AIAA Papers: #96-1670 [1], #98-2260 [2], #98-2261[3], and #99-1924 [4] have been presented at the 2nd, 4th, and 5th AIAA/CEAS Aeroacoustics Conferences respectively. A paper [5] was published in the AIAA Journal in March, 1997, a paper [6] was published in the Proceedings of the 136th Meeting of the Acoustical Society of America in October, 1998, and a paper on an invention [7] was published in the NASA Technical Briefs in June, 1996.

2) Patents and Inventions: Two patents were granted on July 20, 1999 [8], and January 12, 2000 [9], and three patent applications [10-12] have been accepted and awarded with NASA Certificates of Recognition (for example, see Figures 1 and 3).

3) Reports/presentations without publications: Twenty-two reports have been presented at NASA LaRC, GRC and Hampton University. These include 12 reports at the Workshop/Seminar: "NASA Langley Research Center- Hampton University Partnership in Fluid Mechanics and Acoustics" on May 15-16, 1997, at Hampton University. This workshop included participation of HU students, leading scientists and professors from NASA LaRC, Hampton University and TsAGI, **a)** Drs: Dennis M. Bushnell, John M. Seiner, Jay C. Hardin, Kenneth S. Brentner, Douglas M. Nark, Yuri A. Plotnikov (NASA LaRC), **b)** Profs: Vladimir M. Kouznetsov, Boris M. Efimtsov, Victor F. Kopiev (TsAGI), Aron S. Ginevsky; **c)** Profs: Mikhail Gilinsky, Abol. G. Miamee, Alkesh Punjabi, Frank P. Kozusko, and others. 5 reports have been presented at the Acoustics Seminars in the TsAGI, Moscow, on November 17-22, 1997, during a visit of the US Team members to Russia (Drs. M. Gilinsky and J.M. Seiner).

4) Proposals and Grants: Since 1996, 5 proposals were submitted by the FM&AL members for NASA programs, 5 for the CRDF, one for the AFOSR, and one for the NSF. A NASA Partnership Award for the project: "Mixing, Noise and Thrust Benefits Using Corrugated Designs" was granted (NAG-1-1936); two NASA Faculty Awards were granted in January, 1999 (NAG-3-2249) and in January, 2000 (NAG-3-2422). A CRDF Award #RE2-136 (1996-99) and a Young Investigator Program Award for a 3 months visit of the Russian scientist, Dr. Sergey A. Chernyshov, to the HU FM&AL (03/99-05/99) have been granted. A new CRDF one-year grant for joint research between NASA GRC-Hampton University-Institute of Mechanics at the Moscow State University (Russia) was awarded in March, 2000.

5) Interaction with other institutions: At the present time, the FM&AL interacts with several US and foreign institutions, and conducts joint research projects or exchanges by consultations with some of them. The main institutions' and appropriate scientists, employees of these institutions, are: **NASA Langley Research Center**, Drs: Dennis M. Bushnell, Joe W. Posey, Lucio Maestrello, Douglas M. Nark, Christopher L. Romsey, Mrs: Charles R. McClinton, David E. Reubush, Robert Grandle, et al.; **NASA Glenn Research Center**, Drs: Isaiah M. Blankson, Robert C. Hendricks, Grigory Adamovsky, et al.; **Mississippi State University,** Drs: John M. Seiner, Michael K. Ponton, Larry S. Ukeiley et al.; **North Carolina A&T State University,** NASA Center for Aerospace Research, Dr. Frederick Ferguson et al., **Toronto State University, Canada,** Aerospace Center, Dr. Alexander L. Gonor et al.; in Russia: **Moscow State University** (Academicians: Gorimir G. Chernyi, Vladimir A. Levin, Alexander I. Zubkov, Samvel S. Grigoryan, Drs: Alexander I. Shvets, Valery G. Gromov, Vladimir I. Sakharov, et al.), **Central AeroHydrodynamics Institute**, TsAGI, Moscow, Drs: Vladimir M. Kouznetsov, Victor F. Kopiev, Sergey A. Chernyshov, Boris M. Efimtsov, et al.); **Central Institute of Aviation Motors**, TsIAM, Drs: Alexander N. Krayko, Natalia I. Tellyaeva, Vladimir A. Vinogradov, et al. .

6) Laboratory improvement:

a) At the present time, the basic foundation for the FM&AL at Hampton University has been established, i.e. good facilities for theoretical and experimental research. The FM&AL's headquarters is located in room #503 in the Olin Bldg. Four computers with necessary supporting equipment are installed in the office: three SGI Indigo-2 connected with a Laser printer, ADP QMS Inc., and a Dell Computer connected with a Canon C5500 Fax/Printer/Scanner/Copier. All computers have access to the HU network and to the NASA GRC and LaRC networks through Internet. A Tektronix Phaser 850 color printer is connected with all computers through Internet as well. All SGI computers are provided with modern software such as F90 compilers and TECPLOT-8 of the AMTEC Inc. for visualization and representation of numerical results. The FM&AL computer lab will extend its capacities by purchasing several additional software packages and supplies using the current grant and some additional HU funds.

b) The Hampton University Low Speed Wind Tunnel (HU/LSWT) has been installed in the Experimental Hall, (room #124) in the Olin Bldg. The tunnel is loaned to the FM&AL by NASA and is a small-scale working model of the large scale LSWT at the NASA LaRC. Basically, the HU/LSWT is for experimental aerodynamic problem investigations. However, the HU/LSWT will be employed for aeroacoustic testing as well. Thus, the original HU/LSWT construction was changed in accordance with the size of the Experimental Hall and with the purpose of noise reduction from the fan motor and for reduction of the vibration influence of this motor on the main portion of the wind tunnel with the test section.

7) Theory and Numerical Simulations: Analytical theory, numerical simulation, comparison of theoretical with experimental results, and modification of theoretical approaches, models, grids etc. have been conducted for several complicated 2D and 3D nozzle and inlet designs using NASA codes based on full Euler and Navier-Stokes solvers: CFL3D, CRAFT, GODUNOV, FM&AL and others.

8) Experimental Tests: Experimental acoustic tests have been conducted for different Bluebell nozzle designs and nozzles having Screwdriver or Axisymmetric Plug and Permeable Shells in the small and large anechoic facilities at the NASA LaRC and TsAGI, Moscow. A small scale model of the NASA Low Speed Wind Tunnel (LSWT) has been installed in the Experimental Hall of the HU FM&AL (June, 1999). Preliminary preparations for experimental tests have been made.

9) Teaching and Training: Four lecture courses were conducted for graduate students of the Mathematics and Computer Science Departments in the field of Fluid Mechanics and Acoustics, and eight supported courses were conducted for undergraduate students of the Engineering and Technology School in the field of multi-phase flows. Three students were involved in the experimental work for wind tunnel installation and test preparation.

10) Students Research Activity: In accordance with the HU-NASA LaRC agreement, 25% of this grant's funds were transferred to the NASA LaRC for direct educational goals at the center. Simultaneously, FM&AL were not permitted to involve HU's students in research project fulfillment using this grant's funds. Nevertheless, 8 graduate and undergraduate students were involved in this project with funding from other supporting grants, NAG-1-1936, and others.

11) Financial Distribution: The total amount of the FAR Award, $225K, was spent uniformly during the 3 years, and ~40% provided salaries for the main researchers involved in this project's fulfillment: Drs: M. Gilinsky, D.M. Nark, F.P. Kozusko, and J.C. Hardin. About $4.5K was spent for travel, and $2K for equipment purchases.

REFERENCES

1. Gilinsky, M., and Seiner J.M., 1996, Corrugated Nozzles for Acoustic and Thrust Benefits of Aircraft Engines, CEAS/AIAA Paper 96-1670, 2nd Joint CEAS/AIAA Aeroacoustics Conference, May 12-15, 1996/Penn.St. PA.

2. Gilinsky, M., Seiner J.M., and Backley, F.D., 1998, Screws, Propellers and Fans Based on a Möbius Strip, AIAA Paper # 98-2260, 4th AIAA/CEAS Aeroacoustics Conference, June 2-4, 1998, Toulouse, France.

3. Gilinsky, M., Kouznetsov, V.M., and Nark, D.M., 1998, Acoustics and Aeroperformance of Nozzles with Screwdriver-Shaped and Axisymmetric Plugs, AIAA Paper # 98-2261, 4th AIAA/CEAS Aeroacoustics Conference, June 2-4, 1998, Toulouse, France.

4. Gilinsky M., Blankson I.M., Kouznetsov V.M., and Chernyshov S.A., 1999, Aeroperformance and Acoustics of the Nozzle with Permeable Shell, AIAA Paper # 99-1924, 5th AIAA/CEAS Aeroacoustics Conference, May 10-12, 1999, Seattle, WA.

5. Seiner, J.M., and Gilinsky, M.M., 1997, Nozzle Thrust Optimization while Reducing Jet Noise, AIAA Journal, Vol.35, No. 3, pp. 420-427.

6. Kouznetsov, V.M., Karavosov, R.K., and Gilinsky, M., 1998, Advanced Methods for Jet Noise Suppression, 136th Meeting of the Acoustical Society of America, October 12-16, 1998, Norfolk, VA.

7. Gilinsky, M. and Seiner, J.M., 1996, Propellers and Fans Based on the Möbius Strip, NASA Technical Briefs, June, 1996.

8. Seiner, J.M., and Gilinsky, M., 2000, Undulated Nozzle for Enhanced Exit Area Mixing, US Patent, granted on January 12, 2000.

9. Seiner, J.M., and Gilinsky, M., 1999, Jet Nozzle Having Centerbody for Enhanced Exit Area Mixing, US Patent #5,924,632.

10. Seiner, J.M., and Gilinsky, M., 1996, A Bluebell Nozzle for Improving the Mixing of Exhaust Jets with Ambient Air, Patent Application for Invention Disclosure, June 12, 1996, NASA Case No. LARC-15215-1.

11. Gilinsky, M., and Seiner, J.M., 1996, Blade of a Rotary Machine Having Improving Efficiency, Patent Application, NASA Case #LaRC-15146-1, June, 12, 1996.

12. Seiner, J.M., and Gilinsky, M., 1996, Corrugated Separate Flow Co-Annular Nozzle, Patent Application for Invention Disclosure, NASA, Case No. 15518-1, June 12, 1996.

13. Seiner, J.M., and Gilinsky, M., 1995, Nozzle Thrust Optimization while Reducing Jet Noise, AIAA Paper 95-2191, 26th AIAA Fluid Dynamics Conf., June 19-22, 1995/San Diego, CA.

APPENDIX

SOME DETAILS OF RESEARCH RESULTS

I) Corrugated Nozzle Designs

Based on the research studies conducted by Drs. M. Gilinsky and J.M. Seiner at the NASA LaRC during 1993-96, a new method has been developed which permits the design of jet exhaust nozzles with optimized thrust while achieving jet noise reduction. This method led to the conception of the Bluebell, Chisel, and Telescope nozzles and to nozzles with Screwdriver-Shaped centerbodies (plug), and permeable nozzles and shells. Preliminary results are very interesting to the industry and require further analysis and testing. We continued to investigate these designs to determine the optimal characteristics of such designs. Several such designs are shown in Figures 4-12.

1.1 A Bluebell Nozzle. The Bluebell nozzle can be constructed on the base of any plain nozzle: axisymmetric round conical, elliptical, triangular, rectangular, 2D convergent-divergent (CD), etc. Figure 2 shows representative examples of 8-, 6-, and 4-petal Bluebell nozzles (from left to right in the upper row) which were made and tested in the small anechoic chambers at the NASA LaRC and TsAGI, Moscow. The Bluebell nozzles are designed on the base of a round convergent-divergent nozzle, and have sinusoidal lip line edges, i.e. the nozzle edge distance from the nozzle throat changes sinusoidally versus azimuth angle with variation in amplitude. The cross sections of the nozzle divergent part also are limited by sinusoidal curves as a function of polar angle, so that the variation in amplitude increases along the nozzle centerline from zero at the throat to the maximum value at the exit. In Figure 4, a 4-petal Bluebell nozzle is shown. Also shown are the schematic representations of two kinds of vortex flow structures that basically influence the jet noise level. These are: **a)** axial counter-rotating vortices formed by corrugated nozzle cross section (2), and **b)** longitudinal vortices (3) which form into ring shaped mixing layers at the boundary of two flows, hot engine jet exhaust and ambient air flow.

In particular, acoustic tests at the NASA LaRC and TsAGI, Moscow, of corrugated nozzles have shown some acoustic and thrust benefits relative to traditional round nozzles (see lower model in Figure 2). For example, Bluebell nozzles (upper set in Figure 2), which were obtained by 3D nozzle design incorporating a corrugated cross section nozzle shape with a sinusoidal lip line nozzle edge, can provide an acoustic benefit up to 4dB with ~1% thrust augmentation. This effect was explained as being the result of the corrugated design producing more efficient mixing of the exhausted jet with ambient air. (see [1,5] for details).

Many typical examples of numerical simulation results were illustrated in the papers [1,5]. These simulations included a wide interval in nozzle geometry, in particular, variation of the petal and corrugation coefficients, their frequencies, exit Mach numbers, and baseline nozzle variation. In the last case, we examined conical and optimal axisymmetric nozzles, which provided maximum thrust for the fixed convergent part. The main numerical results concerning thrust optimization were conducted for exhaust Mach number M_e=1.5, and presented as the ratio of the Bluebell nozzle relative to the baseline nozzle thrust vs nozzle geometric parameters.

Three approaches and numerical codes were used to examine accuracy of numerical results. The first is based on the "viscous-inviscid interaction". The Euler approximation was used for definition of the "external" inviscid flow outside a thin boundary layer. Numerical simulations of subsonic and transonic flows in the convergent portion of the nozzle were conducted by an implicit upwind 2nd order numerical scheme (ENO-version) for solution of the full unsteady Navier-Stokes equations, as incorporated in the CRAFT-Tech code. The supersonic flow into the divergent portion was simulated by the more economical and well-known fast 2D and 3D Krayko-Godunov marching schemes. In the 2D boundary layer, the Patankar-Spalding algorithm was employed since the Mach number can change significantly along the exit lip line. On one hand, lateral flow reduces pressure at the wall, but on the other hand, it also reduces the "effective" boundary layer thickness. In addition, recently, the more effective NASA CFL3D numerical code has been used. The nozzle thrust calculation is based on a full Navier-Stokes solver or full Euler codes. Grid preparation and optimization are conducted using GRIDGEN and our own codes. These numerical simulations, in common, confirmed our conclusion about possible thrust benefits using the Bluebell nozzle design by comparison with the baseline round nozzle.

1.2 A Chisel Nozzle. To improve Bluebell Nozzle acoustic characteristics, a Chisel nozzle was proposed and analyzed. An example of such is the 8-petal nozzle shown in Figure 6. The nozzle cross section contour is a piecewise function. The general idea of this design is similar to that of the Bluebell nozzle: to favor a gradual formation of a swirl flow downstream with minimal thrust loss, and in some cases, with thrust augmentation. Wing aerodynamic theory helps to construct such a three-dimensional nozzle. A gas flowing along a nozzle wall produces a larger thrust if corrugation convexities are contracted to the nozzle exit (as in the case of an aerofoil or a diamond-shaped wing). The cavity (convexity) width also linearly increases (decreases) downstream from zero (maximum) at the throat to the maximum (zero) at the nozzle exit. For such a configuration, two expanded flows near the nozzle wall flow into two neighbouring cavities to meet each other at some angle α, mutually penetrate and more effectively mix. The flow impulse on the lateral area of the convexities increases the resulting nozzle thrust.

A Chisel nozzle may be made with smooth corrugations, like a Bluebell nozzle. Therefore, sharp edges of a Chisel nozzle's cavities and convexities can be smoothed, for example, by substitution of the discontinuous periodic function by the first terms of its Fourier series or by variation of the cavity (convexity) width nonmonotonically by a corresponding parabolic function. This curve is characterized by a variation amplitude coefficient and has a point of inflection. It also makes possible other dependencies. Lastly, it is interesting to consider a convexity in the form of a "reverse V-shaped wing" with triangular cross section contour. Geometric parameter variations change thrust and aeroacoustic characteristics of the Chisel nozzle and optimization of these geometric parameters is the general object of numerical simulations, which will precede acoustic and aerodynamic experimental tests. For description of Chisel nozzle geometry in detail, see the paper [1].

A Chisel nozzle is very convenient to use to design a Telescope nozzle (see below). Such an example is shown in Figure 7, where the main external design (1), Chisel nozzle, is based on the cone of the angle $\alpha=10^{\circ}$ and the internal design (2) has a conical surface. This nozzle can significantly increase nozzle thrust.

1.3 A Telescope Nozzle. A divergent flow can act on a plate or airfoil inserted into a flow so that a resulting force is directed against the flow. This effect is used for thrust by supersonic nozzles. Conversely, a uniform flow produces only drag for bodies and airfoils. Inserting a conical or wedge-shaped nozzle inside the divergent part of the external nozzle so that the integral of the pressure on the low side of the inserted surface is greater than on the upper side produces increased thrust. There is an optimal angle of the plate element that provides the maximum thrust for each point of a divergent flow. The most efficient internal design is produced from a pattern that looks like a telescope with extending tubes. The optimal number of internal designs is defined through dependence on the Mach number at the nozzle exit (M_e). Telescoping designs must be located so that the compressible waves formed by the interaction of flow with such a design would be passed on to the upper side of the next lower telescoping part. The best result will be produced by such a set if the external design inclination increases downstream. The computations show that a significant thrust benefit from the Telescope nozzle occurs with external telescoping design, using either wedge, conical or optimal contour shapes, and also in the case of a plug application.

The analytical theory was developed and numerical simulations were conducted. Results were described in [13]. In particular, it was shown that by the usual deformation of a single axisymmetric or 2D nozzle it is possible to obtain only an insignificant thrust augmentation, even using optimal nozzle shape, i.e. ~1-4% by comparison with the usual conical (wedge-shaped) nozzle. A Telescope nozzle can increase thrust significantly more.

One possible Telescope nozzle embodiment is shown in Figure 9, where the external nozzle is constructed by specifying the fixed contour $z=z(x)$ in an zx-plane and the cross section contour is described by the super-elliptical equation with an exponent n depending on the axial coordinate x. For the Telescope nozzle in Figure 4, this exponent $n(x)$ increases from 2 to 10 downstream from the throat to the exit. Two plane internal designs are located symmetrically supported by the holders into the external design. Several other embodiments and examples of Telescope nozzle applications are given in the papers [1,13]. They show that the internal design location is very important, i.e. its inclination and length. The numerical simulation results also show that a significant thrust benefit from the Telescope nozzle occurs with external telescoping design, using either wedge, conical or optimal contour shape, and also in the case of a plug application. The benefit is significant for Telescope nozzles with several internal components. For example, the thrust augmentation for a conical nozzle with three internal components can approach ~25 to 50 percent. This benefit increases for short nozzles with increase of cone angle.

Analogous results were obtained for 2D wedge-shaped Telescope nozzles. Comparison of the thrust for the single nozzle and Telescope nozzle with four internal components in Figure 13 has shown that thrust augmentation can reach ~75%. For hypersonic nozzles, the augmentation can be even more. The working efficiency of a Telescope nozzle grows as Mach numbers increase as well as external design angle. Note that the main Telescope nozzle analytical and numerical simulation results were obtained on the basis of the Euler approximation without boundary layer corrections or full Navier-Stokes numerical simulation. However, some designs were tested recently using the NASA CFL3D code based on the full Navier-Stokes equations. These tests in common have confirmed all conclusions made earlier.

Note that telescoping internal designs can provide thrust benefits not only for divergent nozzle portions but, also, for inlets of an air-breathing propulsion system. In this case, energy of the turned flow along the forebody wall can be used for creation of additional thrust. As in the previous problem, the mutual locations, sizes and angles of the internal plates (thin airfoils) are very important for efficiency of the application. Optimal values of geometric parameters were determined by multi-parametric numerical simulations based on the above prescribed modified marching K-G code. An effect of four thin airfoils installation at the minimal cross section (nearby of the corner point) is illustrated in Figure 14. Here Mach contours and corresponding streamlines are shown for the 2D Telescope inlet with the wedged forebody. This design provides a forebody drag reduction of 25%.

1.4 A Two-contour Bluebell nozzle with plug. One of the well studied concepts for jet noise reduction is the inverted velocity profile jet (IVP). In this concept, the outer flow of a co-annular nozzle is designed to operate at a higher velocity than the interior core flow. The IVP's efficiency was estimated from 2 to 11 PNdB noise reduction and ~1-1,5% thrust loss by different research data. These tests were conducted statically. In forward flight, both characteristics are worse. Better results were obtained by using the Combined Source Suppression (CSS) concept, which, for this case, uses joint application of an IVP and an ejector. These combinations give additional acoustic benefits, but they add new performance problems. Therefore, the further improvement of the IVP approach is a desirable goal.

To reduce jet noise through enhanced mixing with ambient air, we have proposed in [1,9] to apply a Bluebell nozzle shape for one or both nozzle end-portions. For this discussion, assume that the lip line edge of this nozzle is located on the cylindrical surface at the radius r_e and its axial coordinate x_e is defined as before by the sinusoidal equations. The defined surface is formed by the family of rectilinear intervals between an initial circle in cross section and the end sinusoidal curve on the cylindrical surface. We compared the usual two-contour axisymmetric round nozzle with rectilinear walls and the two-contour Bluebell nozzle, which has the same lateral area of each end-portion as was analyzed previously. This is equivalent to the same nozzle weight.

Figure 5 illustrates the two two-contour Bluebell nozzles based on the same baseline nozzle. In the first figure, the internal design has 4 petals, external-8 petals. The same idea is applicable for the supersonic divergent nozzle portion. Such a design was denoted as a Telescope Bluebell nozzle. An example of such nozzle is shown in Figure 8. The theoretical research and numerical simulation of subsonic and supersonic flows into the two-contour nozzle and jet exhaust were conducted, and the main results are based on numerical simulation of the steady nozzle-jet flowfield by the CFL3D code for viscous gas flow, and inviscid approximation for sound wave propagation using the Tam's approach for far field noise calculation. Experimental acoustic tests at the NASA LaRC have shown significant benefits of two contour Bluebell nozzle application (unpublished results).

1.5 Screwdriver Centerbody (plug). A screwdriver body shape belongs to a family of surfaces formed by rectilinear intervals joining corresponding points of two different closed curves in space. A screwdriver body uses a circle as an initial curve and one or several crossing rectilinear intervals as an end curve. Usually, these intervals are symmetrically located relative to a body's axis of symmetry. A 4-petal screwdriver centerbody is shown in Figure 10. Here a convergent nozzle 1 contains a cylindrical centerbody and downstream, after a throat, it transfers to a screwdriver shape. There are several geometric parameters which define the centerbody: number of petals, petal's size and centerbody length. The axisymmetric centerbody with conical or optimal contour in a meridional plane can be taken as a baseline centerbody for comparison and for definition of screwdriver centerbody efficiency.

In the case of a 4-petal centerbody, four symmetrical flow regions occur between two neighbouring petals.Threedimensional flows form downstream with swirls at the local symmetry line. These four anti-symmetric swirls meet each other after this point at some angle and form large vortices downstream. This enhances mixing of the jet exhaust with ambient air and can cause jet noise reduction. This 3D centerbody shape also favors flow stagnation at the local symmetry line which increases pressure on the lateral surface of the centerbody. For the same reason, such a 3D flow produces a thinner boundary layer than the usual axisymmetric flow. As a result, we can expect the minimal thrust loss and, in some cases, even thrust augmentation through screwdriver centerbody application by comparison with a baseline conical centerbody.

The US patent [9] for this design and some its modifications was granted. This design was compared with the baseline axisymmetric design with the same cross section area distribution along the nozzle axis. Both designs were tested experimentally and numerically. The acoustic tests were conducted in the anechoic chamber of the TsAGI, Moscow. 3D numerical simulations of the gas flow inside the nozzle and jet exhaust were conducted at Hampton University using the NASA CFL3D numerical code based on the full Navier-Stokes equations and several turbulence models. The main results of this research were presented in the report [3]. The conclusion is: to obtain essential acoustic and thrust benefits by this design application, it is necessary to move the corrugated portion of the plug upstream from the external nozzle exit. That could not be realized in the tests that were conducted and will be addressed in future research. Also these tests have shown that, even in these non-optimal conditions, the SCR nozzle produces almost the same noise as a baseline nozzle having similar aeroperformance as well as some constructive advantage.

We can obtain a similar benefit in the case of a 2D nozzle through the application of linear surfaces. Such a nozzle is a 2D analogue of an axisymmetric Screwdriver centerbody. An individual element of such a construction is shown in Figure 11. The nozzle contains a rectangular throat. A 2D plug is made with straight lines which join points on the throat horizontal side with the vertical interval at the nozzle (or plug) edge. Such elements can be multiply repeated. This forms a cellular nozzle. As in the previous case of an axisymmetric flow, two anti-symmetric swirls form at the lower straight lines of two neighbouring "ravines". These ravines meet each other at the edge on the vertical interval. Two crossing swirl flows create large vorticity downstream.

There is another modification of a corrugated centerbody based on Chisel shaped design. Such a nozzle with 8-petal Chisel centerbody is illustrated in Figure 12. In this case, the convexity (cavity) height is changed as a parabola, its value is null in the boundary points, i.e. at the throat cross section and at the end of centerbody, and its maximum value is reached at the average point of this interval.

1.6 Permeable Nozzles and Shells. This concept was proposed by Dr. M. Gilinsky for jet noise reduction, described in two proposals for NASA programs, and investigated jointly with the Russian team under current and CRDF grants. The main results were presented in the paper [4]. Several simple experimental tests of a spraying system were conducted at the NASA LaRC. One such system is shown in Figure 15. These tests have shown appreciable jet noise reduction when an additional cylindrical permeable shell was employed at the nozzle exit. Based on these results, additional acoustic tests were conducted in the TsAGI anechoic chamber AK-2 (Figures 16 and 17). These tests examined the influence of permeable shells on the noise from a supersonic jet exhausting from a round nozzle designed for exit Mach number, M_e=2.0, with conical and Screwdriver-shaped centerbodies. The results show significant acoustic benefits of permeable shell application, especially for overexpanded jets by comparison with impermeable shell applications. The noise reduction in the overall pressure level obtained was up to 5-8%. Numerical simulations of a jet flow exhausting from a convergent-divergent nozzle designed for exit Mach number, M_e=2.0, with permeable and impermeable shells were conducted at Hampton University. Two numerical codes were used. The first is the NASA LaRC CFL3D code for accurate calculation of jet mean flow parameters on the basis of a full Navier-Stokes solver (NSE). The second is the numerical code based on Tam's method for turbulent mixing noise (TMN) calculation. Numerical and experimental results are in good qualitative agreement. Mach contour comparisons for two cases of simulation results for impermeable (K_p=0) and permeable (K_p=0.2) nozzles with two nozzle pressure ratios, NPR=6.31 and 9.47 respectively, are illustrated in Figure 18. This comparison shows essential weakening of internal barrel shocks in the underexpanded jet due to the permeability of the shell.

The main conclusion of the previous research of corrugated nozzle designs is: It is necessary to develop new general theoretical/numerical simulation approaches for the general study of the influence of surface boundary corrugation characteristics on the flow structure (turbulence regime and level, vortices, mixing etc.) and level and directivity of the noise produced.

II. MOBIUS STRIP CONCEPT

A concept for improving the working efficiency of propellers and screws was proposed in the invention disclosure of Drs: M. Gilinsky and J. M. Seiner in 1993 and patent application was sent to NASA in 1996 [11]. NASA Technical Briefs has published the note [7], which presents a short description of this invention.

3.1 Möbius Strip modification shapes. The concept is based on the Möbius strip-one-side surfaces. There are several embodiments of such shapes. Each of them can be optimal for different applications in different surrounding media. In short, in this and the next section, we will describe the idea of the invention and first positive experimental results. For details, one can see the invention description [11], note [4], and paper [2].

The main goal of the invention is to reduce rotated element drag and, simultaneously, to increase the area for capture of the still medium without increasing the power needed for rotation. Such a surface can be the Möbius strip, a one-sided surface. The Möbius strip has been proposed as the basis for optimally shaped airplane and boat propellers, fans, helicopter rotors, mixing screws, coffee grinders, and concrete mixers. The ambient medium can be air, water, concrete, coffee beans etc. Conventional (non-Möbius) devices of this type consist mostly of two-sided blades, which are not optimal.

A Möbius strip is made by giving a half twist to a strip of elastic material, then joining the ends to obtain a smooth surface. This design is one-sided in the sense that in principle, one can trace out a continuous line along the strip from any point on its surface to any other point on the surface, without leaving (for example, through a border) or penetrating the surface. The one-sided, smooth shape of a Möbius strip provides a large capture area while generating the least possible turbulence in three-dimensional flow, and thus maximizes working efficiency. Several possible modifications are shown in Figure 19a. Möbius design screws are based on the super-elliptic contour in a meridional plane.

3.2 Möbius shaped screws for mixers. All industrial companies who are interested in the invention [11] agree to participate in funding of research, development and joint marketing. However, these companies require preliminary experimental and numerical simulation proofs, that such designs can be effective and adapted to the company's product. As yet, we have only been able to conduct simple, inexpensive tests. Several Möbius shaped screws for the middle class of the kitchen mixers have been made and tested. Some of them are shown in Fig.19a,f. These pairs are mounted in the mixer, which was established on the top of vessels filled with water and small plastic particles on the bottom. The rotation speed of the screws was increased smoothly by the voltage regulator, and power expenditure was measured by the Digital Wattmeter. These are shown on the right and left of the vessel respectively in Figures 19b-d. When rotation speed mounted to a definite value, the particles acquire a motion, rise up and become involved in vortex motion with the water and mixing is accomplished. The power value corresponding to this mixing start characterizes efficiency of the mixer. The tests have shown that the mixer with the Möbius shaped screw pair (right in Fig.19a) is most efficient, and saves more than 30% of the electric power by comparison with the standard (left in Fig.19a). The video film about these tests can be used with scientific-popular goals, for teaching, and with commercial goals. In particular, the discovered effect can be applied in the manufacture of liquid semiconductors.

The current strategy and necessary documents were worked out in the regular working meetings of the LaRC JNT and Technology Application Group (TAG) with HU's researchers and administration. The memorandum of agreement for commercialization of the invention between NASA LaRC-Hampton University-Company was written and adopted. The agreement includes the invention development, applications, marketing, joint patents etc.

Note that this work was only a preliminary start for the future benefit of NASA and HU. At the present time, there are not any sources of funding to conduct analogous preliminary experimental research for cooling, propellers, fans, and other applications that require essentially more expense.

III. Computer System and Low Speed Wind Tunnel at the HU/FM&AL

The last couple of years proved highly successful in the creation of the basic foundation for the FM&AL at Hampton University, i.e. good facilities for theoretical and experimental research. At the present time, the FM&AL's headquarters is located in room #503 in the Olin Bldg. Several illustrative views of this office with the FM&AL members at work are shown in Figures 20-23. Four computers with necessary supporting equipment are installed in the office: 3 SGI Indigo-2 workstations each of its has a R4400 processor, 200MHz, 128MB RAM, 6GB Hard Disk, and 20" Monitor. These UNIX based computers and Microsoft based Dell Computer are connected with a Canon C5500 Fax/Printer/Scanner/Copier, and Tektronix Phaser 850 color printer. All computers have access to the HU network and to the NASA GRC and LaRC networks through Internet. All SGI computers are provided by the modern software such as F90 compilers and TECPLOT-8 of the AMTEC Inc. for visualization and representation of numerical results. The FM&AL computer lab will extend its capacities by purchasing several additional software packages and supplies using the current grant and some additional HU funds.

The Hampton University Low Speed Wind Tunnel (HU/LSWT) is installed in the Experimental Hall, (room #124) in the Olin Bldg. A common view of this tunnel and and working section in the experimental hall are illustrated in Figures 24,25. This tunnel has been loaned to the Fluid Mechanics and Acoustic Laboratory by NASA, and is a small scale working model of the large scale LSWT at the NASA LaRC. Basically, the NASA/LSWT is for experimental aerodynamjc problem investigations. However, the HU/LSWT will be employed for aeroacoustic testing as well. Thus, the original HU/LSWT construction was changed in accordance with the size of the Experimental Hall and with the purpose of noise reduction from the fan motor and for reduction of the vibration influence of this motor on the main portion of the wind tunnel with the test section. At the present time, the HU/LSWT has a U-shaped (elbow) configuration with the following characteristics: The test section is **1.08ft** high, **1.08ft** wide, and **1.75ft** long and the tunnel can reach a velocity of **~164ft** per sec. The square entrance and exit cross sections have the same areas equal (in feet) of **0.25x0.25**. Note, that the gas speed in a jet can be increased up to **320ft** per sec. or even more by installation of a nozzle at the entrance with a sufficient safety margin of the wooden test section. In the future, wooden portions of the wind tunnel will be rebuilt using steel. The Reynolds number per foot ranges from 0 to $1x10^5$. The flow in the test section is relatively uniform with a low turbulence level due to the presence of a honeycomb. The test section airflow is produced by a **3**-ft diameter, 4-bladed fan powered by a **3750**-hp direct current motor. The total length of the main wind tunnel with the text section is **11ft**, the length of the portion with the fan is **9.4ft**, and the wide is **3.8ft**. A Pentium PC Computer with a 16MB RAM, 1GB Hard Disk is installed in this room and has access to the HU network. Basically, this computer will serve for automatic processing data of experimental test results obtained in the Low Speed Wind Tunnel (HU/LSWT).

Initially, the HU/LSWT will be used for educational goals as an instrument for aerodynamic measurements in low speed flows. The wind tunnel will also focus on the development of interactive computer based teaching modules for classical aerodynamic problem studies such as: jet flows, flows around bodies and airfoils, boundary layers, vortices, turbulence, methods of visualization and measurement in wind tunnels and other applications. Several computer-based modules will be prepared using the HU/LSWT with the UNIX and Microsoft based computer systems. For example: **1)** Boundary layer development at a plate, cylinder, and sphere; **2)** Structure of round and 2D jet flow and its mixing with surrounding air; **3)** Separation flows in cavities, behind bodies and airfoils; and **4)** Body and airfoil drag and its measurement. Besides the above described classical problems, HU students will be involved in experimental tests of the current and future research projects which are being conducted under NASA and CRDF grants. In particular, Möbius-shaped propellers and screws, body drag reduction by cavities, inlet optimization, etc.

IV. INTERACTION WITH OTHER INSTITUTIONS

At the present time, the FM&AL interacts with several US and foreign institutions, and conducts joint research projects or exchanges by consultations with some of its. The main institutions and appropriate scientists, employees of these institutions, are: NASA Langley Research Center, Drs: Dennis M. Bushnell, Joe W. Posey, Lucio Maestrello, Douglas M. Nark, Christopher L. Romsey, Mrs: Charles R. McClinton, David E. Reubush, Robert Grandle, et al.; NASA Glenn Research Center, Drs: Isaiah M. Blankson, Robert C. Hendricks, Grigory Adamovsky, et al.; Mississippi State University, Drs: John M. Seiner, Michael K. Ponton, Larry S. Ukeiley et al.; North Carolina A&T State University, NASA Center for Aerospace Research, Dr. Frederick Ferguson et al., Toronto State University, Canada, Aerospace Center, Dr. Alexander L. Gonor et al.; in Russia: Moscow State University (Academicians: Gorimir G. Chernyi, Vladimir A. Levin, Alexander I. Zubkov, Samvel S. Grigoryan, Drs: Alexander I. Shvets, Valery G. Gromov, Vladimir I. Sakharov, et al.), Central AeroHydrodynamics Institute, TsAGI, Moscow, Drs: Vladimir M. Kouznetsov, Victor F. Kopiev, Sergey A. Chernyshov, Boris M. Efimtsov, et al.); Central Institute of Aviation Motors, TsIAM, Drs: Alexander N. Krayko, Natalia I. Tellyaeva, Vladimir A. Vinogradov, et al.

In Figure 26 several participants of the Workshop/Seminar: "NASA Langley Research Center-Hampton University Partnership in Fluid Mechanics and Acoustics" on May 15-16, 1997, at Hampton University are shown. 12 reports were presented at this seminar by the leading scientists and professors from NASA LaRC, Hampton University and TsAGI, including: **a)** Drs: Dennis M. Bushnell, John M. Seiner, Jay C. Hardin, Kenneth S. Brentner, Douglas M. Nark, Yuri A. Plotnikov (NASA LaRC), **b)** Profs: Vladimir M. Kouznetsov, Boris M. Efimtsov, Victor F. Kopiev (TsAGI), Aron S. Ginevsky; **c)** Profs: Mikhail Gilinsky, Abol. G. Miamee, Alkesh Punjabi, Frank P. Kozusko, and others. In Figure 27 several participants of US-Russian Team members are shown. They were the main researchers who leaded experimental and theoretical works under the CRDF grant #RE-136. During the visit of the US Team members to Russia (Drs. M. Gilinsky and J.M. Seiner), 5 reports have been presented at the Acoustics Seminars in the TsAGI, Moscow, on November 16-23, 1997.

V. CONCLUSION

The current research is focused on the development of the Bluebell nozzle and Möbius strip concepts through numerical and experimental simulations. The Bluebell nozzle concept, for which a patent application has been filed through NASA, can be utilized as a noise reduction concept for separate flow co-annular nozzle in the NASA AST program. In this aspect, students were involved in tests at NASA and HU experimental and numerical simulation tests. Already Boeing, GE Aircraft Engines and Pratt & Whitney Aircraft and other aviation companies have expressed interest in the development of this concept for subsonic commercial engine technology pending a successful outcome of testing and analysis. The application of the research to the future supersonic US aircraft engine design is also very promising on the basis of the preliminary positive results of the experimental and numerical simulations. The main problems, as proposed and formulated at the initiation of the NASA FAR program in 1996, have all been resolved by FM&AL team members during the period of performance reported herein. In particular, in this period, the Fluid Mechanics and Acoustic Laboratory at Hampton University was created and at the present time can be employed to investigate new complicated problems in Aviation and Aerospace Engineering using theoretical, numerical simulation and experimental approaches.

CORRUGATED NOZZLES AND PLUGS

National Aeronautics and Space Administration

Presents this Certificate to:

MIKHAIL M. GILINSKY

Certificate of Recognition

For the disclosure of an invention entitled...

JET NOZZLE HAVING CENTERBODY FOR ENHANCED EXIT AREA MIXING

Chairperson, Inventions and Contributions Board

Date

Fig.1

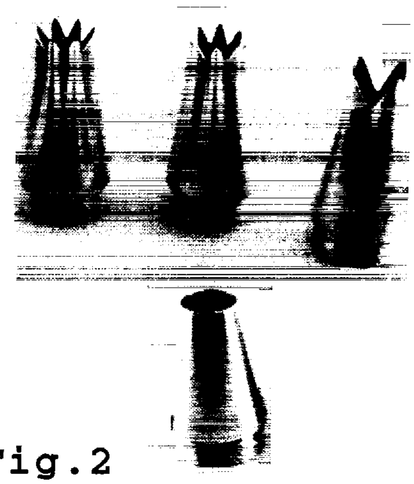
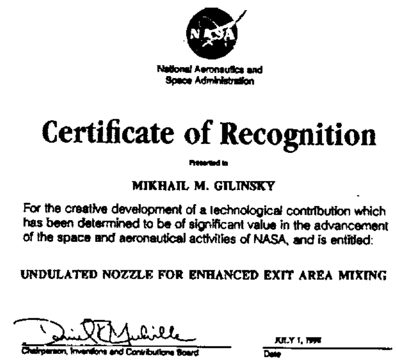


Fig.2



National Aeronautics and Space Administration

Certificate of Recognition

Presented to

MIKHAIL M. GILINSKY

For the creative development of a technological contribution which has been determined to be of significant value in the advancement of the space and aeronautical activities of NASA, and is entitled:

UNDULATED NOZZLE FOR ENHANCED EXIT AREA MIXING

Chairperson, Inventions and Contributions Board

Date

Fig.3

BLUEBELL NOZZLE

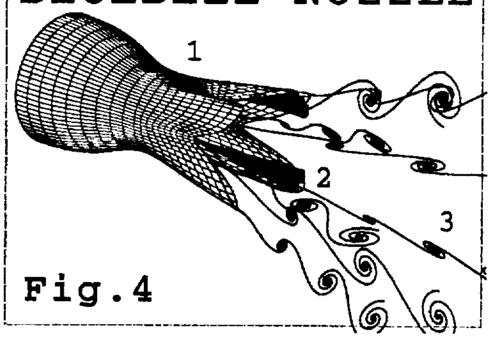


Fig.4

TWO-CONTOUR BLUEBELL NOZZLE WITH PLUG

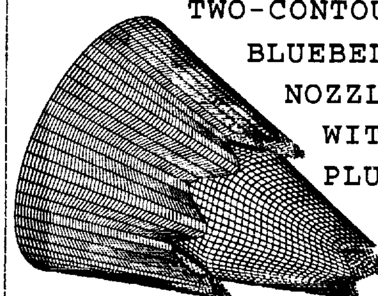


Fig.5

CHISEL NOZZLE

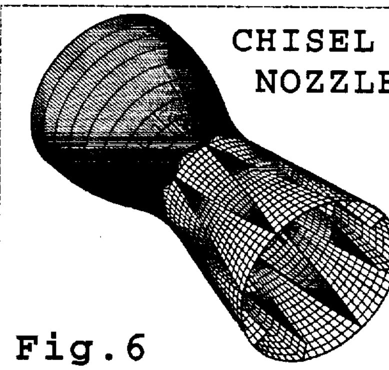


Fig.6

TELESCOPE CHISEL NOZZLE

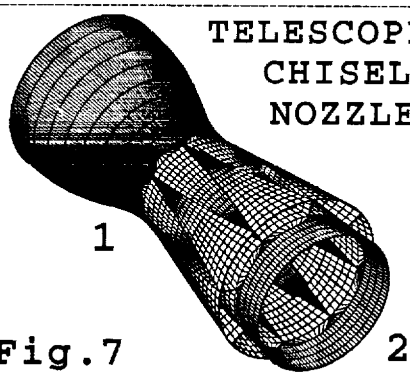


Fig.7

TELESCOPE BLUEBELL NOZZLE

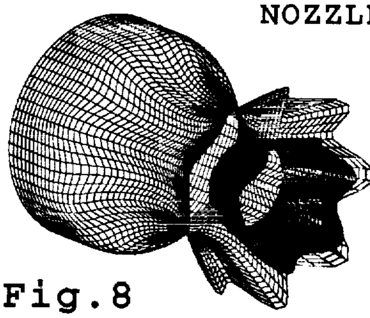


Fig.8

TELESCOPE NOZZLE

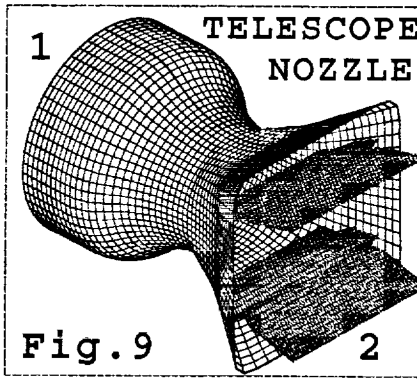


Fig.9

NOZZLE WITH SCREWDRIVER CENTERBODY (PLUG)

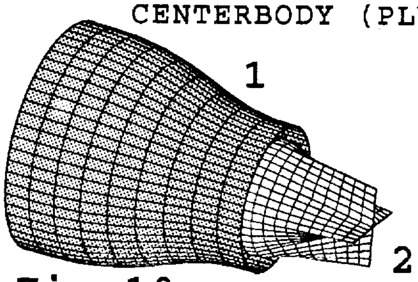


Fig.10

2D SCREWDRIVER NOZZLE

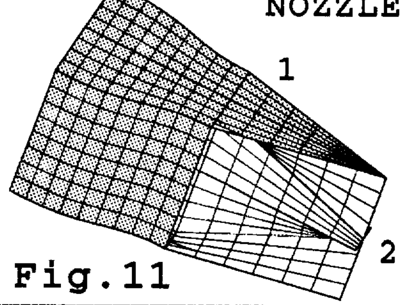


Fig.11

NOZZLE WITH CHISEL CENTERBODY (PLUG)

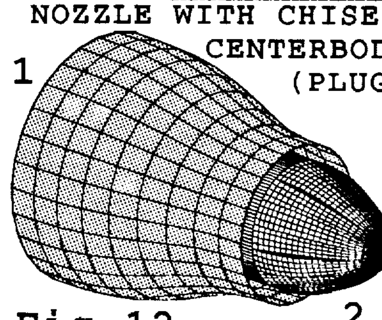


Fig.12

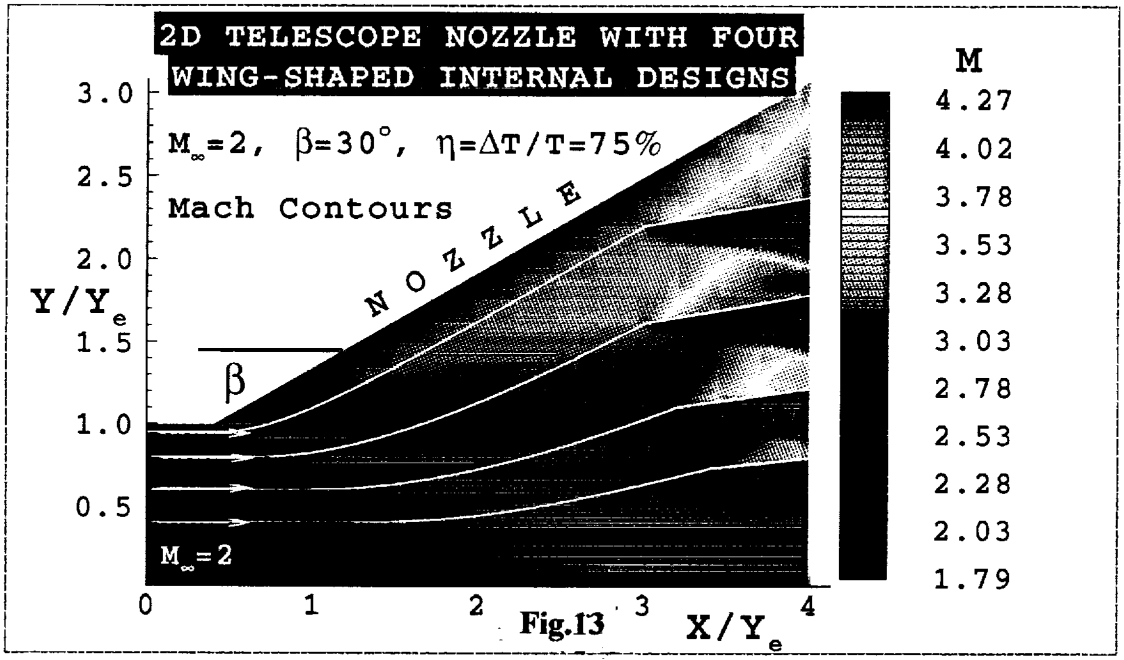

2D TELESCOPE NOZZLE WITH FOUR WING-SHAPED INTERNAL DESIGNS
M∞=2, β=30°, η=ΔT/T=75%
Mach Contours
NOZZLE
β
M∞=2
Y/Ye
X/Ye
M
4.27
4.02
3.78
3.53
3.28
3.03
2.78
2.53
2.28
2.03
1.79

Fig.13

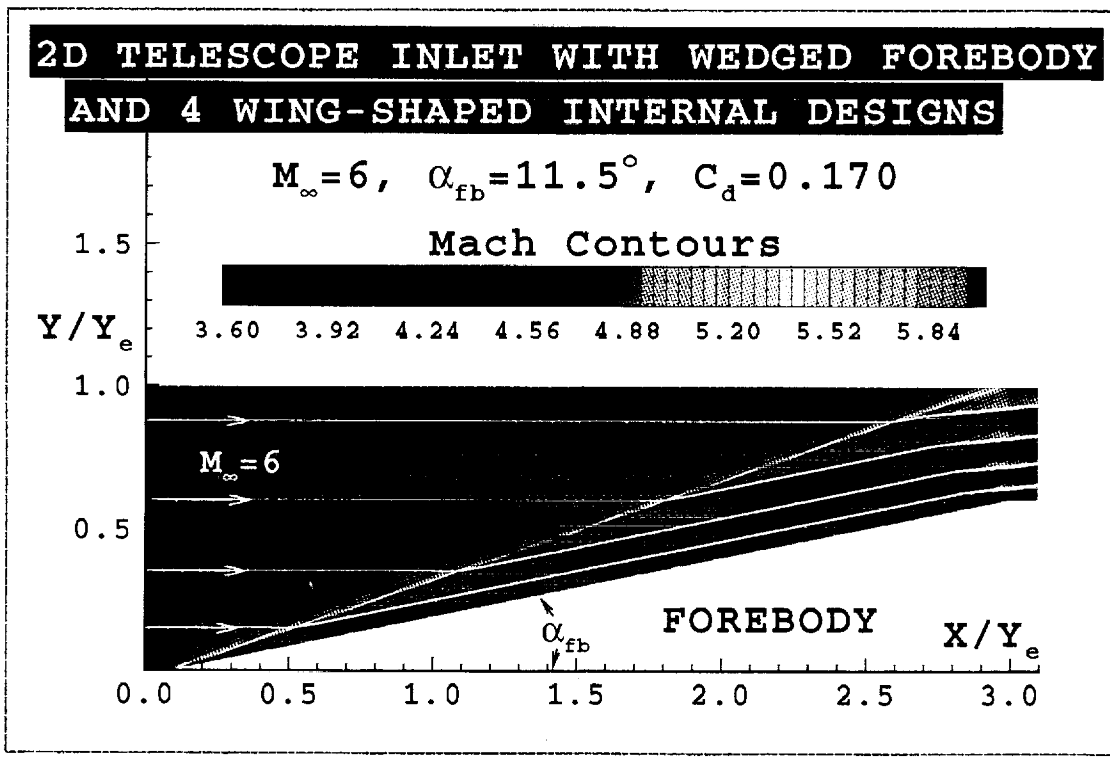
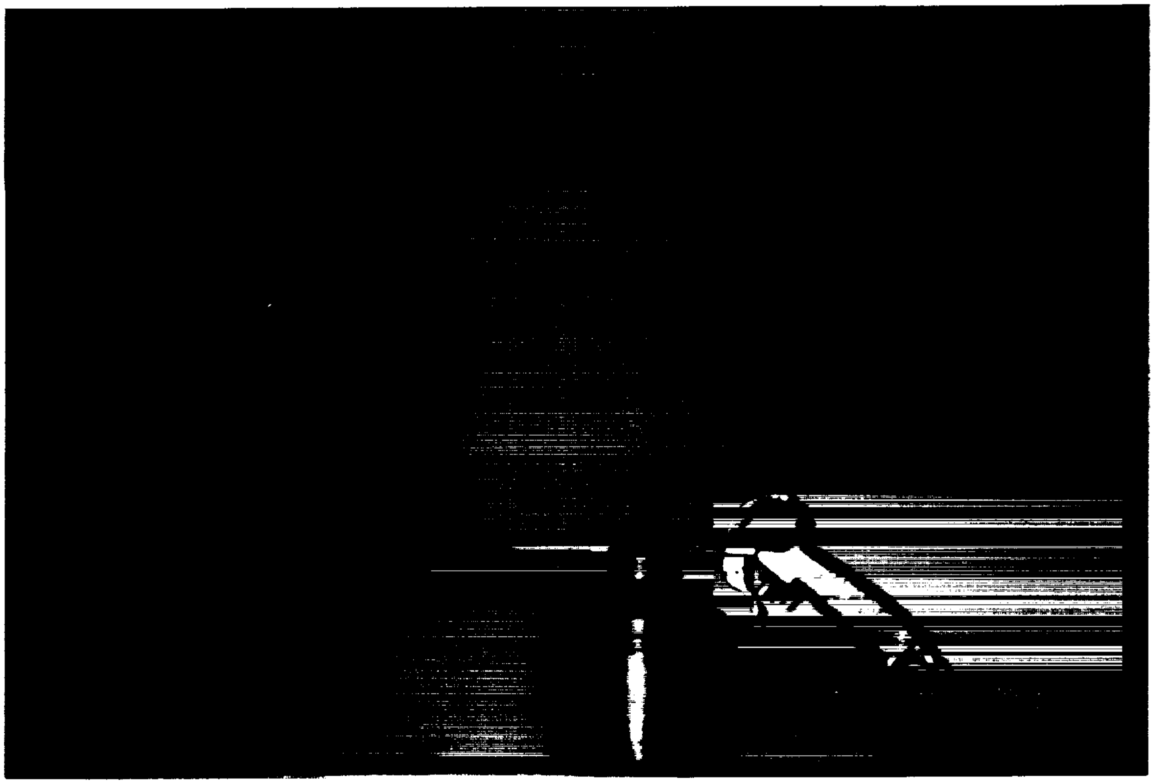
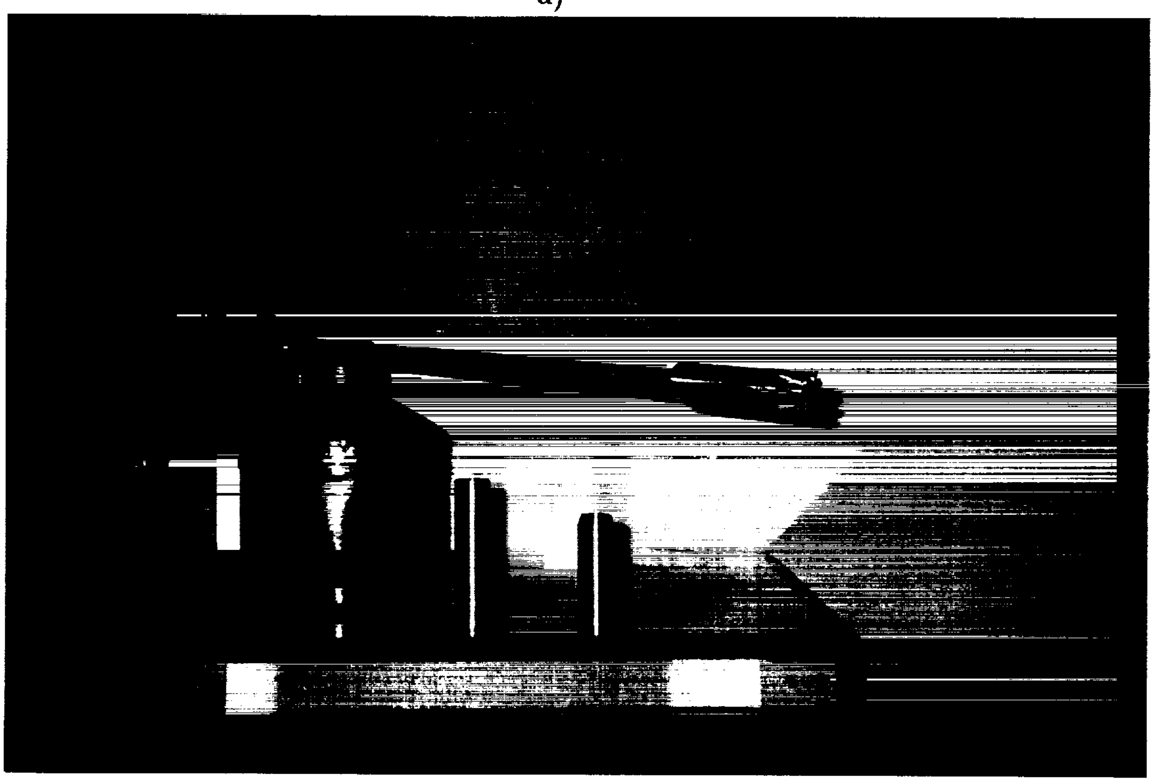

2D TELESCOPE INLET WITH WEDGED FOREBODY
AND 4 WING-SHAPED INTERNAL DESIGNS
M∞=6, αfb=11.5°, Cd=0.170
Mach Contours
3.60 3.92 4.24 4.56 4.88 5.20 5.52 5.84
M∞=6
αfb
FOREBODY
Y/Ye
X/Ye

Fig.14



a)



b)

Fig.15 Two spraying devices with permeable and impermeable shells tested at the NASA LaRC. **a)** the shell is the long small tickness pipe; **b)** the shell is the short large tickness pipe.

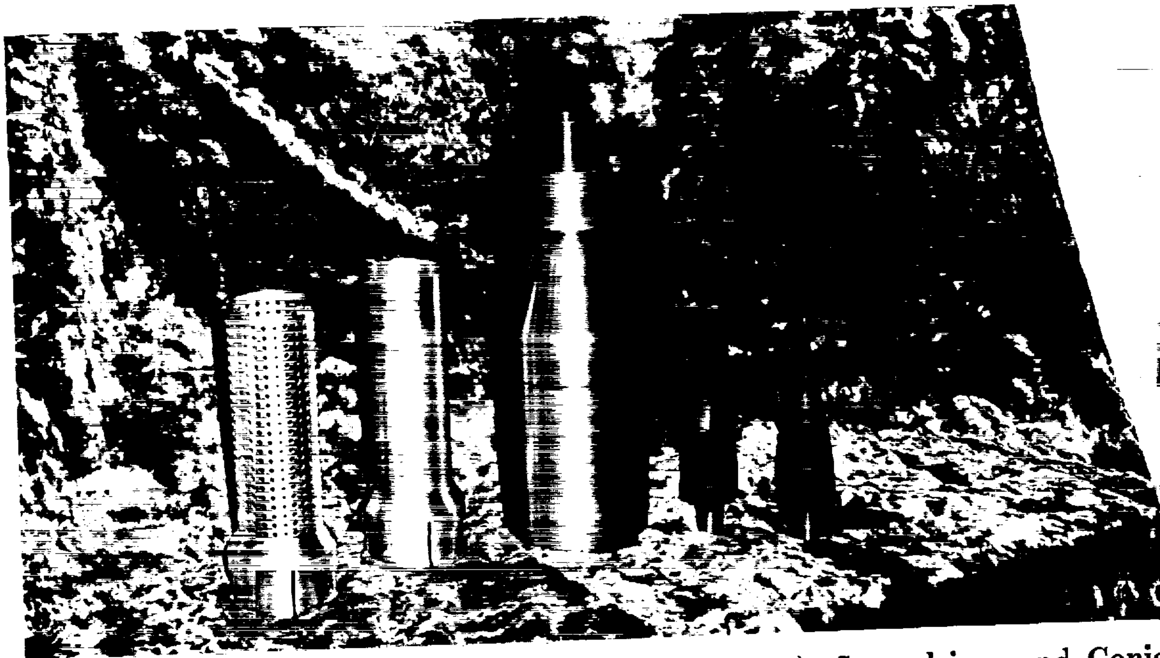


Fig.16 The convergent-divergent (CD) conical nozzle (center), **Screwdriver** and **Conical** centerbodies (right), and solid and perforated shells (left) which were tested in the anechoic chamber AK-2 at the TsAGI, Moscow.

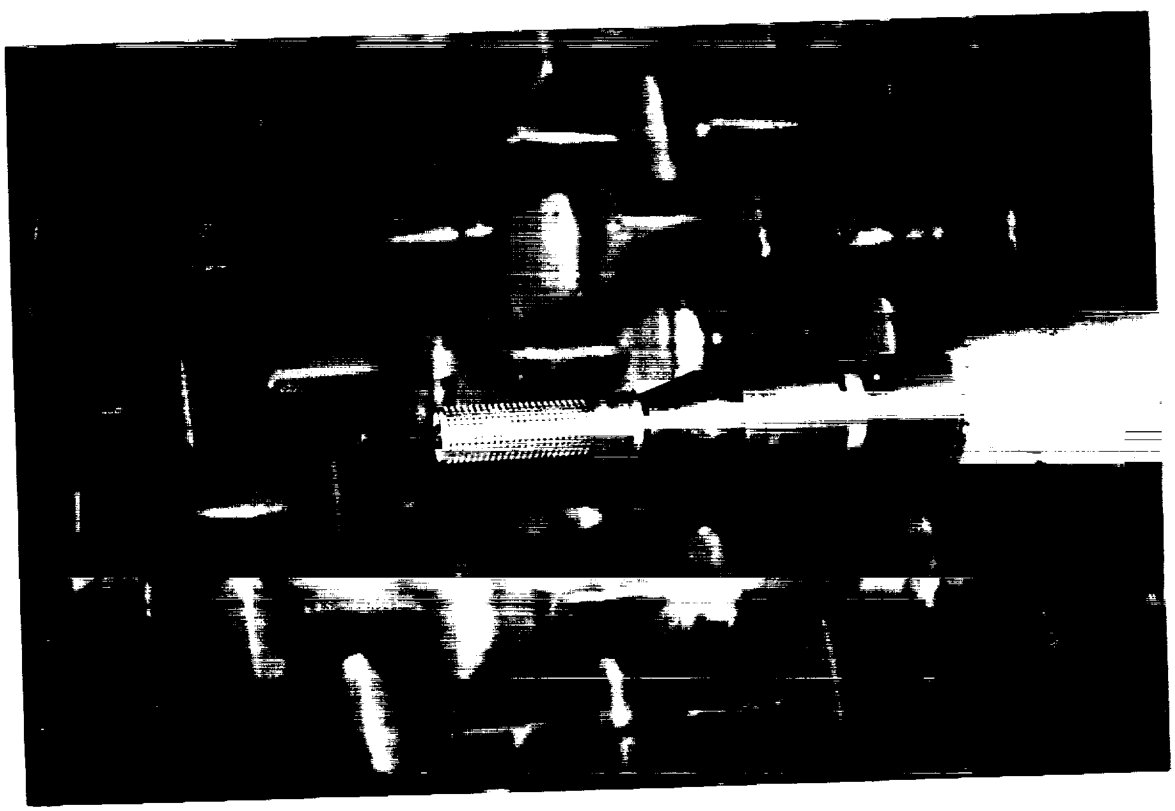


Fig.17 Existing CD conical nozzle with the **Screwdriver** centerbody and perforated shell mounted in the AK-2 (TsAGI, Moscow).

NOZZLE WITH IMPERMEABLE AND PERMEABLE SHELLS

MACH CONTOURS

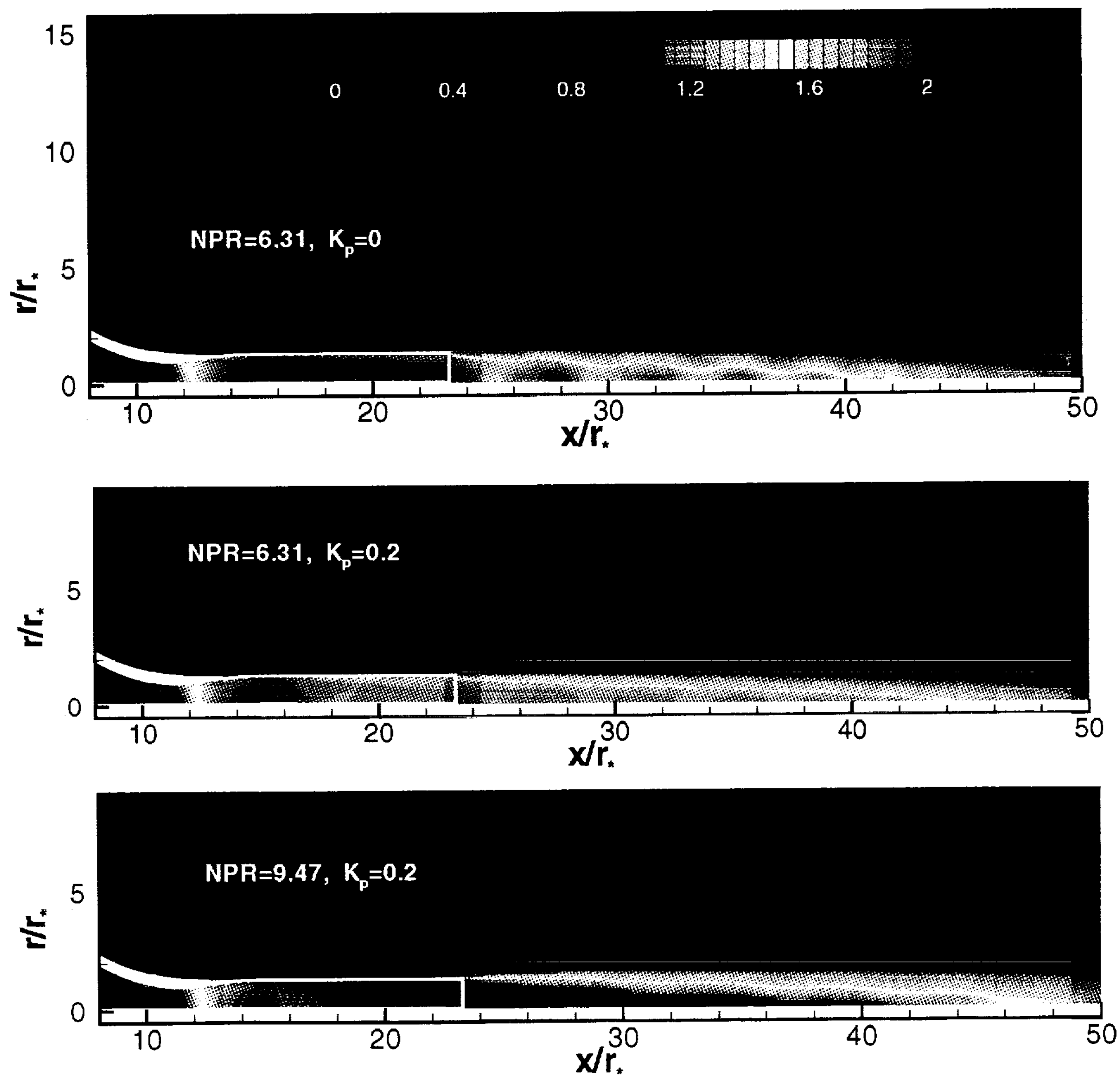
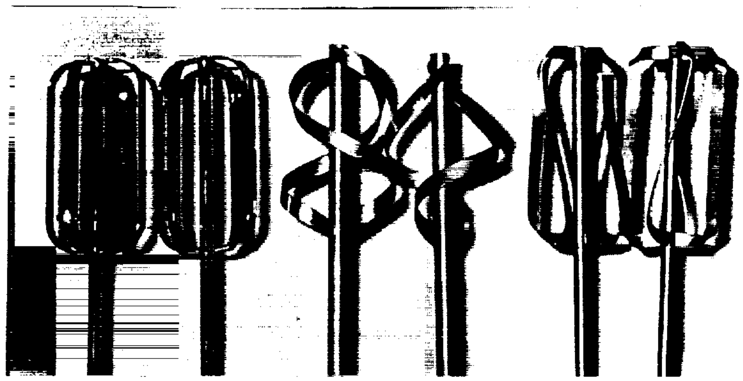


Fig.18 Mach contours for the supersonic flows inside the CD nozzle designed for the exit Mach number, M_e=2.0, and in the exhausting jets for three cases: **a)** the upper picture-impermeable shell (permeability coefficient, K_p=0), overexpanded jet with the nozzle pressure ratio, NPR=6.31; **b)** the middle picture-permeable shell with K_p=0.2 and NPR=6.31; **c)** the lower picture-permeable shell with K_p=0.2, underexpanded jet with NPR=9.47.



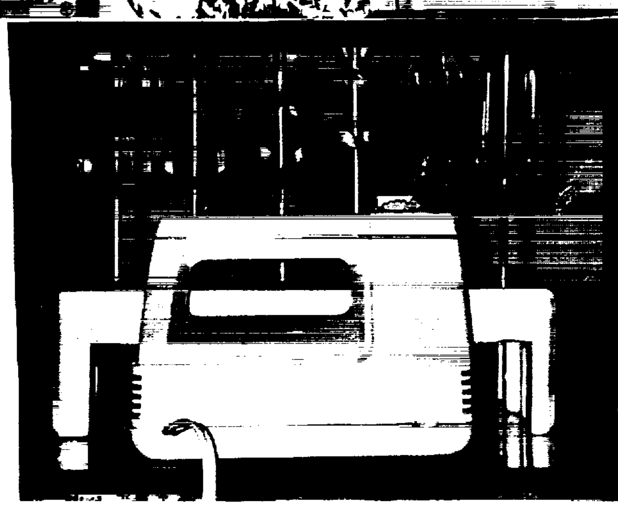
a)

b)

c)

d)

e)



f)

Fig.19 Möbius-Shaped Screws for Mixers.
a)Picture of the three pairs of screws tested. The standard pair is on the left; **b)**-Equipment for tests: voltage regulator (left), mixer over the small vessel with water, plastic particles, and the 1st Möbius screw pair (center), digital wattmeter (right). **c)**-The same as in **b)** but with the 2nd Möbius screw pair. **d)**-The same as in **b)** but with bigger vessel. **e)**-The big vessel with the 1st Möbius screw pair during the test. **f)** The screws and a standard mixer used in tests.

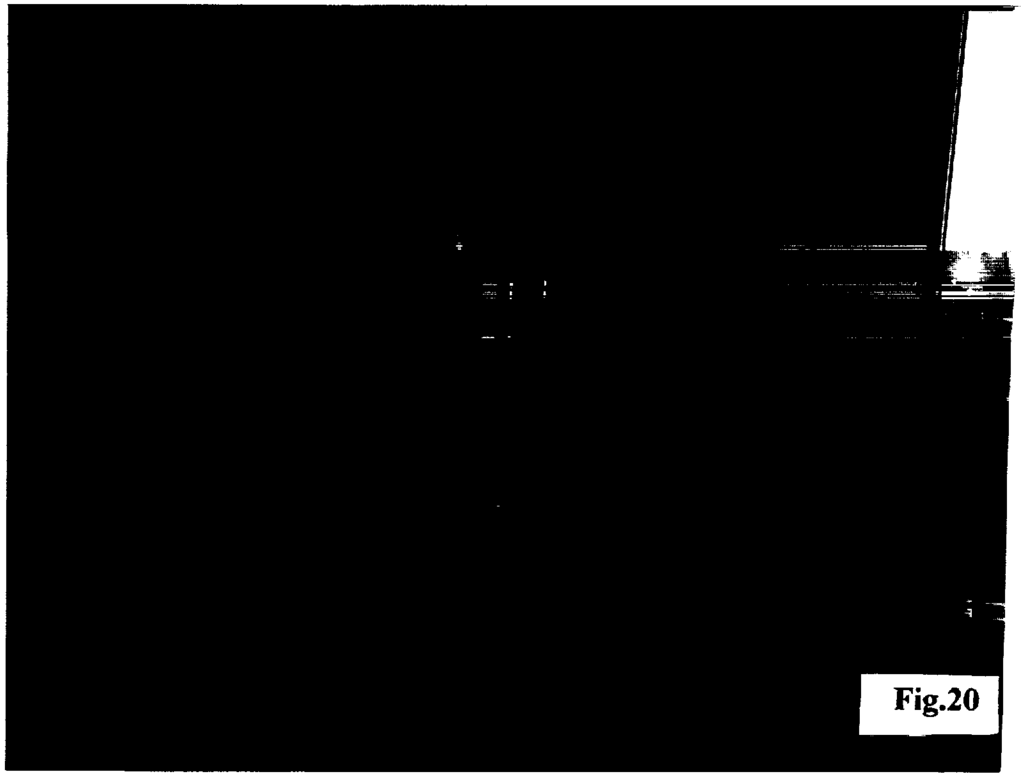


Fig.20

Primary Investigator, Dr. Mikhail Gilinsky in the FM&AL office at his working place.

Fig.21

Principal Investigator, Dr. Morris H. Morgan, Dr. Mikhail Gilinsky, and Graduate Assistant Patel Kaushal. Analysis of numerical results.

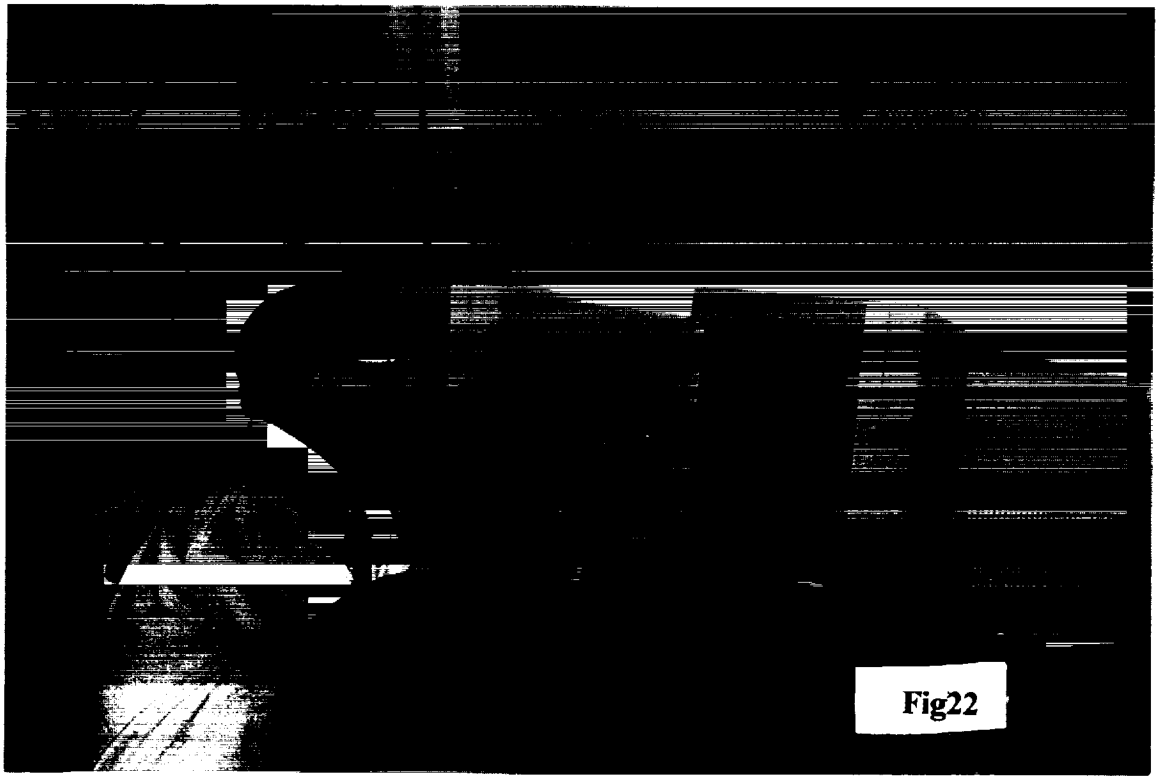


Fig22

Dr. Morris Morgan and Patel Kaushal. Preparation of computer based module.

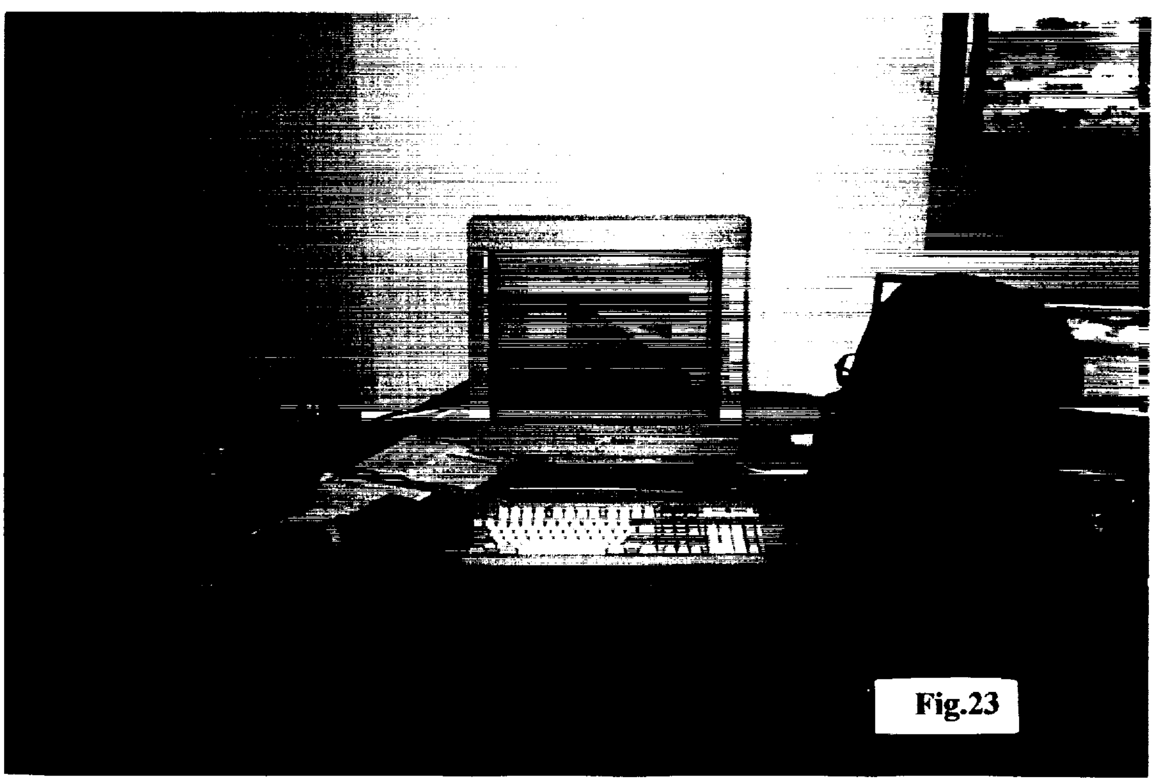


Fig.23

Research Professor, Dr. Mikhail Gilinsky, and Graduate Assistant Gilbert Mosiane. Discussion of numerical results based on the CFL3D code, Lab's INDIGO-2 SGI computer and AMTEC's software TECPLOT.

Fig.24

Hampton University Low Speed Wind Tunnel. NASA has loaned this tunnel to FM&AL.

Fig.25

Dr. Mikhail Gilinsky and Gilbert Mosiane in the Experimental Hall. Preparation of experimental test in the Low Speed Wind Tunnel.

Fig.26

The US (LaRC-HU) and FSU (TsAGI, Moscow, Russia) Team members who participated in the Workshop/Seminar "NASA Langley Research Center- Hampton University Partnership in Fluid Mechanics and Acoustics" on May 15 and 16, 1997.

From left to right, Drs.: Boris M. Efimtsov (TSaGI), Mikhail Gilinsky (HU), Dennis M. Bushnell (NASA LaRC), Victor F. Kopiev (TsAGI), John M. Seiner (NASA LaRC), Vladimir M. Kouznetsov (TsAGI), Sergey Yu. Makashov (TsAGI), Frank P. Kozusko (HU).

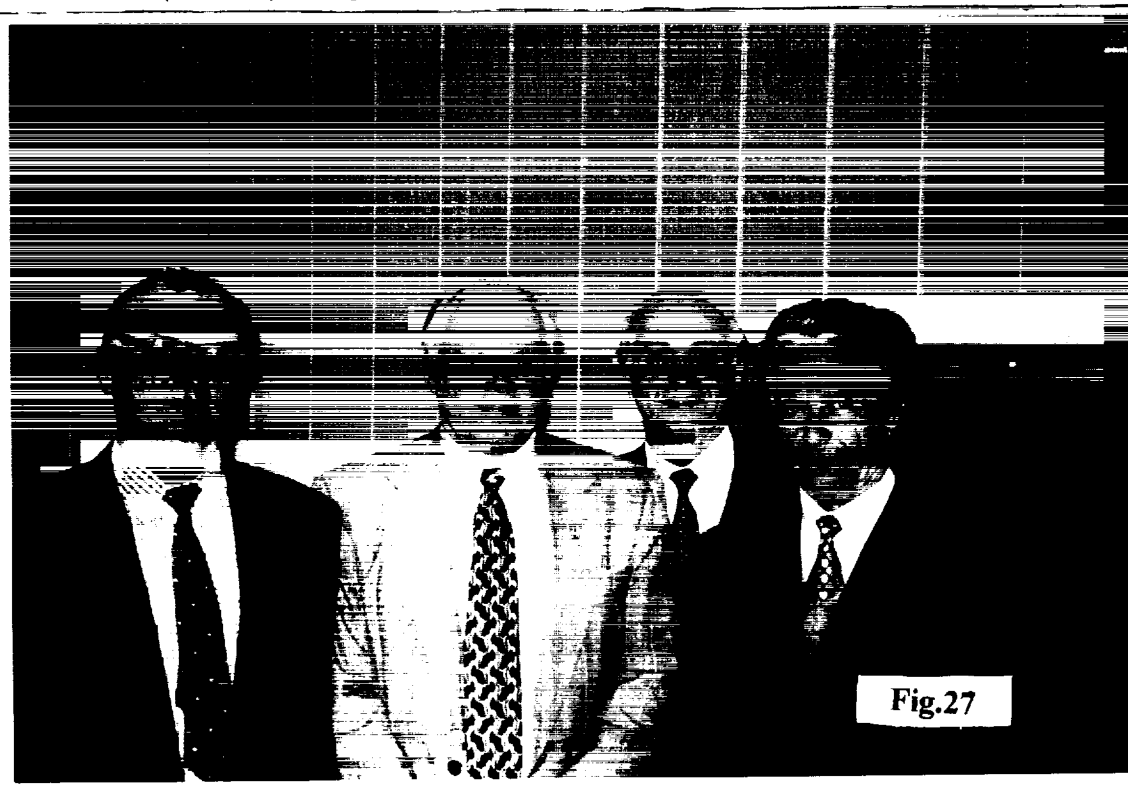


Fig.27

During meeting at the TsAGI, Moscow on November 16-23, 1997.

From left to right: Prof. Vladimir M. Kouznetsov (Chief of the TsAGI Acoustic Division), Dr. John M. Seiner (Leader of the NASA LaRC Jet Noise Team), Dr. Mikhail Gilinsky (Hampton University Research Professor), Anatoly G. Munin (Director of the TsAGI/Moscow Branch).